

## HOT GAS IGNITION TEMPERATURES OF HYDROCARBON FUEL VAPOR-AIR MIXTURES

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### ABSTRACT

Laminar hot air jets of 1/4 to 3/4-inch diameter were employed to determine the hot gas ignition temperatures of various combustible vapor-air mixtures. The combustibles were n-hexane, n-octane, n-decane, a hydrocarbon jet fuel (JP-6) and an adipate ester aircraft engine oil (MIL-L-7808). Minimum ignition temperatures occurred at a fuel-air weight ratio of about 0.5 and were not greatly sensitive to variations of fuel concentration. Moderate variations of jet velocity also had little influence on these ignition temperatures. However, these temperatures decreased with an increase in heat source dimensions (jet diameter) similar to that observed in the hot surface ignition of the hydrocarbon combustibles. Furthermore, it was noted that the hot gas ignition temperatures of the combustibles tended to approximate corresponding auto-ignition and wire ignition temperatures when the size of the heat source and the ignition criterion were the same. Temperature profiles obtained for 1/2-inch diameter hot air jets indicated that the jet temperatures required to produce "hot" flame ignitions and luminous or "cool" flame reactions with these combustibles are of greater significance than the corresponding heat flux values.

### INTRODUCTION

Most of the ignition temperature data available for combustible fluids have been obtained using heated vessels, wires, or tubes as the sources of ignition. A jet of heated air or other gas, if sufficiently hot, can also produce ignition when it comes into contact with combustible gases or vapors. Such an ignition source may be a problem during the rupture of an oil seal in a jet engine or during blasting operations in a coal mine where hot gases are released from the explosives employed. The temperatures at which combustible gas mixtures can be ignited by laminar jets of hot air and inert gases have been determined only in recent years by Wolfhard and others (5,6,7) for hydrogen, carbon monoxide, and various low molecular weight hydrocarbons. The present work was conducted to investigate the hot gas (air) ignition temperature characteristics of several high molecular weight hydrocarbon combustibles mixed with air.

Hot gas ignitions differ from wire ignitions and autoignitions in heated vessels primarily in that surface effects are absent with a hot gas heat source, providing the reaction chamber is relatively large. The hot gas ignition temperatures of hydrocarbon combustible mixtures have been reported to agree generally with corresponding wire ignition temperatures but to be much higher than the autoignition temperatures (AIT's) of the mixtures (7). However, according to our hot surface ignition studies (2) and to the preliminary findings of the present study (3) which are included here, the variation between such ignition temperatures can depend greatly on the size of the heat source and on the ignition criterion used. The hot gas ignition temperature data of this work were obtained with laminar jets of hot air injected into combustible vapor-air mixtures under near-stagnant flow conditions. Data are included on the effects of combustible concentration, jet diameter, and jet velocity for a given size of reaction chamber. Since a relatively stable luminous jet is ordinarily observed prior to these ignitions, temperature profiles of the jets were obtained to compare the heat requirements for the initial luminous or "cool" flame reactions and the

subsequent "hot" flame ignitions with each combustible. The combustibles included n-hexane, n-octane, n-decane, a hydrocarbon jet fuel (JP-6), and an adipate ester aircraft engine oil (MIL-L-7808).

#### EXPERIMENTAL APPARATUS AND PROCEDURES

The apparatus used for the hot gas ignition temperature determinations is shown in figure 1 and, except for some minor modifications, is similar to that employed by Wolfhard (7). Basically, the apparatus consisted of a tubular ceramic furnace that was used to heat the air stream, a cylindrical reaction chamber into which was fed the hot air jet and the combustible vapor-air mixture, and the feed assemblies that provided the desired mixture at a uniform rate. The tubular furnace was wound externally with platinum-rhodium wire and was enclosed in a cylindrical Nichrome\*-wound furnace (3-inch ID). The reaction chamber consisted of a 4-inch diameter Pyrex pipe (26 inches long) that was also heated to maintain the combustible mixture at a given temperature. Narrow slits were located on both sides of the enclosed pipe along its longitudinal axis to permit visual observation of flame propagation. The combustible mixture was fed to the reaction chamber through a "mixing ring" (perforated coil of tubing) located just below the base of the hot jet; a water jacket between the ring and the ceramic tubular furnace helped maintain the mixture at a uniform initial temperature.

The temperatures of the hot air jets were measured with a 33-B&S gage platinum/platinum-10 percent rhodium thermocouple at a point of about 1/4 inch above the jet base; the temperature decreased progressively with the height above the jet base at a rate that was determined in part by the jet diameter and velocity. The temperatures of the combustible mixtures were measured with three thermocouples spaced 3 inches apart as shown in figure 1; recorded temperature differences were usually not in excess of  $\pm 25^\circ$ . A mixture temperature of  $600^\circ$  F was used for the engine oil which contained higher boiling point constituents than did the fuels. The mixture flow rate was  $365 \text{ in}^3/\text{min}$  ( $\sim 1 \text{ in}/\text{sec}$ ), and the jet flow rate was  $185 \text{ in}^3/\text{min}$  ( $\geq 50 \text{ in}/\text{sec}$ ), both at N.T.P. conditions, in the experiments with 1/4, 3/8, and 1/2-inch diameter jets; a jet flow rate of  $365 \text{ in}^3/\text{min}$  ( $\sim 50 \text{ in}/\text{sec}$ ) was used with a 3/4-inch size jet. These jet flow rates were used since they appeared to be optimum for ignition of the mixtures in the 4-inch diameter reaction chamber.

To conduct an experiment, the temperatures of the hot air jet and ambient atmosphere in the reaction chamber were measured initially. The thermocouples were then removed and the combustible mixture was introduced, flowing coaxially with the hot jet. If ignition did not occur, the jet temperature was increased in successive increments until ignition was evidenced by the propagation of flame throughout the combustible mixture. Normally, a small precursor flame or luminous column was faintly visible above the base of the jet prior to ignition (figure 2); this flame extended to a height of 6 inches or less above the jet base and resembled a pale blue "cool" flame. Fuel residence time and fuel-air ratio were also varied to obtain the minimum ignition temperatures with each size of hot air jet. Generally, ignitions occurred in 10 to 60 seconds, although a few took place after as much as 180 seconds from the time the combustible mixture was admitted. The minimum ignition temperature values were repeatable to within  $\pm 25^\circ$ .

Temperature profiles of 1/2-inch diameter jets of hot air were determined with the jets flowing into preheated air and into preheated combustible vapor-air mixtures. For this purpose, the cylindrical reaction chamber was equipped with a probe which

\* Reference to trade names is for information only and endorsement by the Bureau of Mines is not implied.

could be adjusted to make axial and radial temperature measurements at various heights within the hot gas jet. Adjustment of the temperature probe was made by rotating a micrometer in contact with a movable plate supporting the probe. The thermocouple bead of this probe was made with 36-gage platinum/platinum-rhodium wire and was coated with a ceramic material recommended by the Bureau of Standards; addition of the coating resulted in slightly lower ( $\leq 25^\circ$ ) jet temperatures. In making these measurements, jet base temperatures were selected to produce the initial luminous reactions and the subsequent "hot" flame ignitions under the given flow conditions. However, the ignition reactions were usually quenched when the temperature probe was inserted at a distance between 0 and 4 inches above the jet base; under such conditions, ignitions were obtained only when the probe was positioned at distances in excess of about 4 inches above the base of the jet.

All of the neat hydrocarbon fuels used in this work were of chemically pure grade, at least 99 percent pure. The MIL-L-7808 engine oil consisted primarily of adipate diesters which vaporized at temperatures between  $480^\circ$  and  $780^\circ$  F; its flash point was  $435^\circ$  F. The JP-6 jet fuel contained about 85 percent saturated hydrocarbons and 14 percent aromatic hydrocarbons; its flash point was  $100^\circ$  F.

## RESULTS AND DISCUSSION

### Hot Gas Ignition Temperatures

The temperature required to ignite a combustible vapor-air mixture with a jet of hot gas depends on the dimensions of the jet as well as on the composition and velocity of the jet and combustible mixture. Since jets of hot air were used in the present work, the combustible vapor-air mixture was diluted by the air jet, particularly along the interface between the two moving fluids. Accordingly, relatively high fuel concentrations and low jet flow rates should be the most optimum for ignition; low flow rates provide low air dilution rates and long contact times with the combustible which are highly favorable for ignition. The results presented here for n-hexane, n-octane, n-decane, JP-6 jet fuel, and MIL-L-7808 engine oil vapor-air mixtures were consistent in this connection.

Figure 3 shows the variation of the hot gas ignition temperatures with fuel-air weight ratio (F/A) employing 1/2-inch diameter air jets flowing concurrently into the combustible vapor-air mixtures; jet flow rate was  $185 \text{ in}^3/\text{min}$ , and the mixture flow rate was  $365 \text{ in}^3/\text{min}$ . As in hot surface ignition temperature determinations (2), the effect of F/A ratio is seen to be slight except at low ratio values ( $\sim 0.30$ ) where the ignition temperatures tend to increase noticeably as the F/A ratio is decreased. Similar behavior was also noted in the ignition temperature determinations made with 1/4, 3/8 and 3/4-inch diameter hot air jets; figure 4 shows the data obtained for n-decane with the various sized jets. Generally, a F/A ratio of approximately 0.5 was required to obtain the minimum temperatures for ignition. Since uniform mixtures of these combustibles in air usually would not be expected to propagate flame at such high F/A ratios, the observed behavior is probably attributed to the dilution of the mixtures and the elevation of the mixture temperatures ( $\geq 350^\circ$  F) by the hot air jet.

In the above experiments, with the 1/2-inch diameter jet the jet velocity was about  $50 \text{ in/sec}$  ( $185 \text{ in}^3/\text{min}$ ) and the mixture velocity  $1 \text{ in/sec}$  ( $365 \text{ in}^3/\text{min}$ ). Data obtained under other flow conditions are summarized in table 1 from experiments conducted with 1/2-inch diameter jets of hot air and MIL-L-7808 engine oil vapor-air mixtures. It is evident from these data that the influence of jet velocity on minimum ignition temperature was not great for the range of velocities used in these experiments; this behavior is consistent with that reported by other investigators (5). The ignition temperature increased only slightly when the jet velocity was varied from  $36.5$  to  $81.0 \text{ in/sec}$  with a constant mixture velocity of  $1.0 \text{ in/sec}$ . They also

increased slightly when the mixture velocity was varied between 0.7 and 1.5 in/sec; here, the jet velocity/mixture velocity ratio was maintained at a constant value slightly above 50. Although a jet velocity of approximately 50 in/sec was near optimum for ignition of the mixtures with 1/2-inch and 3/4-inch size jets, higher jet velocities were required with 1/4-inch and 3/8-inch diameter jets to provide ideal heat inputs for ignition.

TABLE 1. - Effect of jet and mixture velocity on the minimum hot gas ignition temperature of MIL-L-7808 engine oil with a 1/2-inch diameter hot air jet.  
Fuel-air Weight Ratio - 0.55

Jet Velocity/ Mixture Velocity Ratio	36.5	52.1	52.5	52.7	54.7	81.0
Mixture Velocity, in/sec	1.0	0.7	1.0	1.3	1.5	1.0
Ignition Temperature, °F	1240	1255	1250	1270	1315	1300

Table 2 lists the minimum hot gas ignition temperatures obtained for the hydrocarbon fuel and engine oil vapor-air mixtures with the 1/4, 3/8, 1/2 and 3/4-inch diameter jets of hot air. These data are also shown graphically in figure 5 where the minimum ignition temperature values are plotted against the reciprocal of jet diameter (1/d); a similar plot including hot surface ignition temperatures is shown for the data found with n-decane vapor-air mixtures in figure 6, which is discussed later. As expected, the ignition temperatures of these combustibles decreased consistently as the heat source diameter was increased. However, for n-octane, the decrease was only 30° in varying the jet diameter from 1/2-inch to 3/4-inch. The use of larger size jets was not investigated because dilution effects could be great for the size of reaction chamber employed. For a given jet diameter, the ignition temperature values for the paraffin hydrocarbons increased only slightly with decreasing molecular weight. Also, the values for the JP-6 fuel tend to be the highest, and those for the MIL-L-7808 engine oil tend to be the lowest for jet diameters  $\leq 0.5$ -inch. These results are unusual since the engine oil is a high AIT ( $\sim 750^\circ \text{F}$ ) combustible, whereas the jet fuel is a low AIT ( $\sim 450^\circ \text{F}$ ) combustible like the above paraffin hydrocarbons. However, the trend is consistent with that observed for these materials in autoignition and wire ignition temperature determinations with varying heat source diameters (2). Since the thermal stability of the combustibles at the pertinent temperatures may account for such observations, decomposition studies would be interesting to pursue, particularly with the adipate diesters which largely make up the engine oil.

TABLE 2. - Minimum hot gas ignition temperatures of the hydrocarbon fuels and engine oil (fuel vapor-air mixtures) with various hot air jets.  
Mixture Flow Rate - 365 in<sup>3</sup>/min (N.T.P.)  
Fuel-air Weight Ratio - Optimum for ignition ( $\sim 0.5$ )

Diameter of Jet, inch	Jet Flow Rate, in <sup>3</sup> /min	Ignition Temperature, °F				
		n-Hexane	n-Octane	n-Decane	JP-6	Engine Oil MIL-L-7808
1/4	185	1630	1610	1600	1670	1530
3/8	185	1450	1440	1440	1500	1410
1/2	185	1280	1250	1220	1410	1250
3/4	365	1210	1220	1170	1290	1210

### Comparison of Hot Gas and Hot Surface Ignition Temperatures

A comparison was made of the autoignition, wire ignition, and hot gas ignition temperatures of various paraffin hydrocarbon and JP-6 fuel vapor-air mixtures for cylindrical heat sources of about 0.4-inch diameter. Figure 7 shows the variation of these ignition temperatures with the number of carbon atoms present in each combustible; 12 carbon atoms were assumed for JP-6. The hot gas ignition data for the low molecular weight hydrocarbons are those of Vanpee and Wolfhard (6). They were obtained by injecting hot air jets at  $365 \text{ in}^3/\text{min}$ , as compared to  $185 \text{ in}^3/\text{min}$  for the data from the present study, into pure fuel under near stagnant conditions ( $\sim 1 \text{ in}/\text{sec}$ ). According to the data in table 1, the difference in jet flow rates should not be serious. The autoignition temperatures (2) were determined in a quiescent air atmosphere by injecting liquid fuel into a heated cylindrical Pyrex vessel, 6 inches long. The wire ignition temperatures (2) were also obtained under near stagnant conditions ( $0.15 \text{ in}/\text{sec}$ ) where the combustible mixture was passed over a heated Inconel wire (2 inches long) mounted perpendicular to the axis of flow. Fuel-air weight ratio ( $0.3\text{-}0.5$ ) and fuel residence time ( $> 1 \text{ second}$ ) were optimum for ignition for the data shown.

It is seen in figure 7 that the ignition temperatures generally decrease with increasing number of carbon atoms or molecular weight of the combustible, although all of the data are not consistent. In addition, the hot gas ignition temperatures are about  $200^\circ$  higher than the corresponding wire ignition temperatures and at least  $300^\circ$  higher than the AIT's. Somewhat the same behavior is found in comparing these ignition temperatures at various heat source diameters. Figure 6 shows such a comparison for n-decane vapor-air mixtures. Here, the hot gas ignition temperatures again are the highest, and their variation with the reciprocal of heat source diameter ( $1/d$ ) resembles most closely that displayed by the autoignition temperatures; the wire ignition temperatures tend to display the least variation for  $1/d$  values greater than  $2\text{-inch}^{-1}$ . Such correlations may improve if the diameter as well as the length of the heat source are considered. The criterion of ignition is also important. For example, table 3 shows that luminous or "cool" flame reactions were observed at jet temperatures between  $100^\circ$  and  $200^\circ$  below those required for "hot" flame ignition. In the above correlations, the hot surface ignition temperatures referred to any visible flame whereas the hot gas ignition temperatures referred only to "hot" flame ignitions. Furthermore, the latter temperatures were measured near the jet base and were at least  $200^\circ$  higher than those at the plane where ignition occurred above the jet base (see table 3). Thus, the hot gas ignition temperatures of the given combustibles probably do not differ greatly from their hot surface ignition temperatures when the ignition criterion and the heat source dimensions are the same.

Considering that heterogeneous surface reactions are absent in hot gas ignitions, some variation probably exists between the hot gas and hot surface ignition temperatures of the given combustibles. At the same time, these hot gas ignition temperatures appear to vary somewhat the same as the autoignition or wire ignition temperatures with heat source diameter and with combustible concentration and composition. Even the anomalous hot gas ignition behavior displayed by the ethane and JP-6 fuels in figure 7 was also observed in the autoignition or wire ignition experiments. Apparently, the temperature dependency of the reactions controlling these hot gas and surface ignitions at atmospheric pressure did not vary greatly with the nature of the heat source.

### Thermal Considerations of Hot Gas Ignition

Hot gas ignitions are unique in that the heat source is essentially free of surfaces and the pre-ignition reactions may be observed at relatively high temperatures and long duration (several seconds). Reaction kinetics involving hot gas ignitions of combustible mixtures may be studied by an analysis of rates of heat production within the hot jet (1,4,7). Such information should also be useful in the study of the heat requirements for the formation of "hot" and "cool" flames.

Thermal ignition of a combustible mixture by a hot gas jet should occur at a point in the jet stream where the heat generated by chemical reaction is greater than the heat lost from the system. If radial convection is assumed to be negligible and axial convection to be most important, the heat balance equation can be reduced to the following expression according to other investigators (1):

$$Q = \rho C_p v_y \left[ \frac{\partial T}{\partial y} - \left( \frac{\partial T}{\partial y} \right)_{Q=0} \right] \quad (1)$$

where  $Q$  is rate of heat release by chemical reaction,  $\rho$  is density of the gas jet,  $C_p$  is specific heat,  $v_y$  is axial velocity, and  $T$  is jet temperature. Since  $\rho C_p v_y$  varies slightly with temperature, the heat release can be determined by measuring the axial jet temperature profiles with combustible  $\left( \frac{\partial T}{\partial y} \right)_{Q=0}$  and without combustible present  $\left( \frac{\partial T}{\partial y} \right)_{Q=0}$ . Such measurements were made here with the 1/2-inch diameter hot air jet flowing into preheated air or preheated fuel vapor-air mixtures at 350° F; a mixture temperature of 600° F was used with the MIL-L-7808 engine oil. The jet flow rate was 185 in<sup>3</sup>/min, the mixture flow rate was 365 in<sup>3</sup>/min, and the fuel-air weight ratio was about 0.25. Since the low jet flow rate produced steep axial temperature gradients, the use of equation (1) was only applicable to low jet heights. Furthermore, the  $Q$  values which were determined here should be considered only as relative values because of experimental uncertainties.

The above measurements were made in the center of the hot air jet where the radial temperature gradient was minimum. Figure 8 shows that the radial temperature profiles for the 1/2-inch diameter air jet ( $T_{base} = 1265^\circ \text{ F}$ ) are reasonably symmetrical and are essentially flat up to a radial distance of about 0.05 inch for distances up to 2 inches above the jet base. In comparison, the corresponding axial temperature gradients are much greater because of the low jet flow rates employed here to obtain minimum ignition temperatures.

Figure 9 shows the axial temperature profiles obtained with preheated air and n-decane vapor-air mixtures at jet base temperatures of 1060° and 1265° F. At the lower temperature, heat evolution is not evident, and the curve describing the data with combustible present is below or coincides with the one found without combustible. Jet base temperatures in excess of 1060° F were required to form luminous reactions or "cool" flames. At 1265° F, the curve with combustible present is noticeably above the corresponding one without combustible at distances equal to and greater than 1-1/2 inches above the jet base. Here, a slight increase of jet temperature would be expected to overcome the thermal losses and produce "hot" flame ignition; a jet base temperature of about 1280° F produced ignition without the temperature probe present. Although sampling data of reaction products were incomplete, these data also indicated that the extent of reaction became noticeable at jet heights of about 1-1/2 inches for jet temperatures near critical for ignition. Similar axial temperature profiles were obtained with n-hexane, n-octane, JP-6 fuel, and MIL-L-7808 engine oil vapor-air

mixtures. In all cases, the temperature differences observed with and without combustible became significant at heights equal to or greater than about 1-1/2 inches above the jet base. Motion picture records of the ignition of n-octane vapor-air mixtures indicated that ignition of these mixtures occurs about 3 inches above the jet base with the 1/2-inch diameter jet at 1400° F (figure 10); the height at which ignition occurs can be expected to increase with decreasing temperature.

From the axial temperature profiles, the critical jet temperature and heat flux which may produce "hot" and "cool" flame reactions were determined for each of the combustibles. The reference temperature was taken at 1-1/2 inches above the jet base where initial reaction was noticeable; a higher level was avoided since the jet tended to be less coherent, in which case radial convection could be as important as axial convection. The gas velocity required in equation (1) was determined from photographs of dust particle tracks of dust entrained in the jet stream and illuminated at selected time intervals. A particle velocity of 73 in/sec was obtained near the center of the jet at distances between 1 and 2 inches above the jet base. In table 3, one observes significant differences between the temperatures which define the two ignition conditions for each combustible. However, the axial heat flux values ( $AQ_{=0}$ ) vary little since the terms  $\rho C_p v_j$  and  $T/y$  in equation (1) were not sensitive to moderate temperature changes. Thus temperature controls the hot gas ignitions to a greater extent than the rate of heat input; this behavior is not unusual for a heat source of relatively large diameter.

TABLE 3. - Critical temperature and heat flux for "cool" flame or luminous reactions and "hot" flame ignitions with 1/2-inch diameter hot air jet flowing into various combustible vapor-air mixtures.

Jet Flow Rate - 185 in<sup>3</sup>/min  
Mixture Flow Rate - 365 in<sup>3</sup>/min  
Fuel-air Weight Ratio - 0.25 to 0.30

Combustible	T <sub>base</sub> °F	T <sub>1</sub> <sup>1/</sup> °F	AQ <sub>=0</sub> ×100 Btu/in <sup>3</sup> -sec	T <sub>base</sub> °F	T <sub>2</sub> <sup>1/</sup> °F	AQ <sub>=0</sub> ×100 Btu/in <sup>3</sup> -sec	Q <sub>2</sub> <sup>2/</sup> Btu/in <sup>3</sup> -sec
n-Hexane	1350	1100	5.55	1455	1190	5.60	1.25
n-Octane	1150	900	5.35	1330	1085	5.50	1.25
n-Decane	1060	750	5.30	1265	1065	5.50	2.15
JP-6 Fuel	1265	1035	5.45	1415	1195	5.55	2.45
MIL-L-7808							
Engine Oil	1320	1130	5.55	1415	1155	5.55	0.60

- 1/ Jet temperatures above which "cool" (T<sub>1</sub>) and "hot" (T<sub>2</sub>) flame ignitions can occur; measured at 1-1/2 inches above jet base.  
2/ Heat release determined from axial convection with and without combustible ( $AQ_{\neq 0}$  -  $AQ_{=0}$ ) at T<sub>2</sub>.

The rates of heat release (Q<sub>2</sub>) in table 3 correspond to temperature rises between 10° and 40° F which were observed at the jet height of 1-1/2 inches. If equation (1) is applicable, a temperature rise of about 160° to 180° F would be required to obtain a heat balance between the heat release rates and the axial convective heat losses (A) and thereby produce ignition. Indeed, temperature rises as high as about 140° have been observed in other similar experiments conducted at temperature conditions near optimum for ignition. Ordinarily, ignitions resulted before temperature rises of this magnitude were realized. Although such axial temperature measurements can be utilized to indicate the possibility of ignition, the use of equation (1) in this connection is more

applicable at relatively high jet flow rates which tend to produce uniform jets and small axial temperature gradients. Accordingly, similar data are presently being obtained at a jet flow rate of 365 in<sup>3</sup>/min to examine the reaction kinetics involved in the hot gas ignitions of the given combustibles.

#### CONCLUSIONS

The hot gas ignition temperatures of various hydrocarbon fuel and engine oil vapor-air mixtures decreased with increasing diameter of the hot air jet. These temperatures are not greatly dependent on fuel-air ratio and jet flow rate. They also do not differ greatly from hot surface ignition temperatures for comparable heat source diameters. The formation of "hot" flames and luminous reaction zones or "cool" flames in these hot gas ignitions appear to depend more on jet temperature than on rate of heat input.

#### REFERENCES

1. Bruszak, A. E., D. Burgess, and M. H. J. Wijnen, Reaction Kinetics in Hot Gas Ignition of Ethane Air. *Combustion and Flame*, v. 7, September 1963, p. 245.
2. Kuchta, J. M., A. Bartkowiak, and M. G. Zabetakis, Hot Surface Ignition Temperatures of Hydrocarbon Fuel Vapor-Air Mixtures. Presented at the 148th Meeting of American Chemical Society, Chicago, Ill., September 2, 1964.
3. Kuchta, J. M., R. J. Cato, and M. G. Zabetakis, Comparison of Hot Surface and Hot Gas Ignition Temperatures. *Combustion and Flame*, (Letter to Editor), v. 8, December 1964, p. 348.
4. Marble, F. E., and T. C. Adamson, Jr., Ignition and Combustion in a Laminar Mixing Zone. *Selected Combustion Problems*, v. 1, Butterworths Scientific, Inc., London, 1954, p. 111.
5. Vanpee, M., and A. E. Bruszak, The Ignition of Combustible Mixtures by Laminar Jets of Hot Gases. BuMines Rept. of Inv. 6293, 1963, 84 pp.
6. Vanpee, M., and H. G. Wolfhard, Comparison Between Hot Gas Ignition and Limit Flame Temperatures. *ARS Jour.*, v. 29, July 1959, p. 517.
7. Wolfhard, H. G., The Ignition of Combustible Mixtures by Hot Gases. *Jet Propulsion*, December 1958, p. 798.
8. Zabetakis, M. G., A. L. Furno, and G. W. Jones, Minimum Spontaneous Ignition Temperatures of Combustibles in Air. *Ind. and Eng. Chem.*, v. 46, October 1954, p. 2173.

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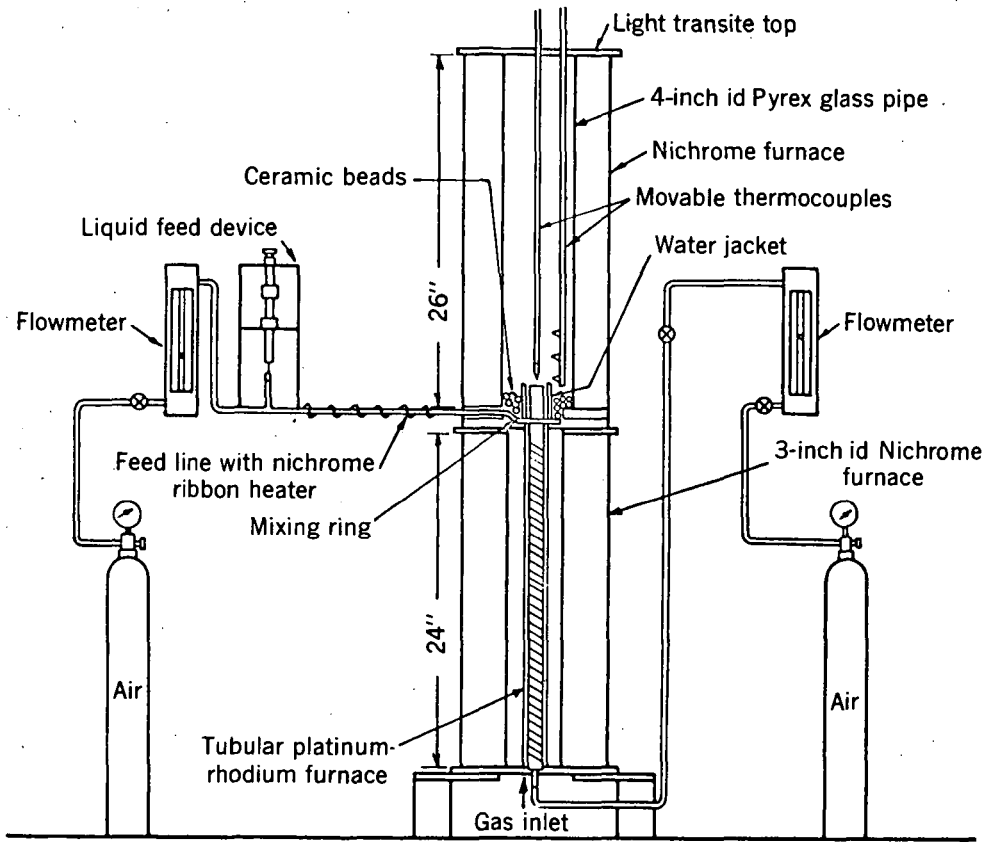


Figure 1. - Hot gas ignition temperature apparatus.



Figure 2. - Precursory flame formed in pre-ignition reaction of 1/4-inch diameter hot air jet (1670° F) with a uniform octane-vapor-air mixture at 350° F.  
Jet flow rate - 185 in<sup>3</sup>/min      Fuel-air weight ratio - 0.14  
Mixture flow rate - 365 in<sup>3</sup>/min      Scale: 1 inch = 0.935 inch

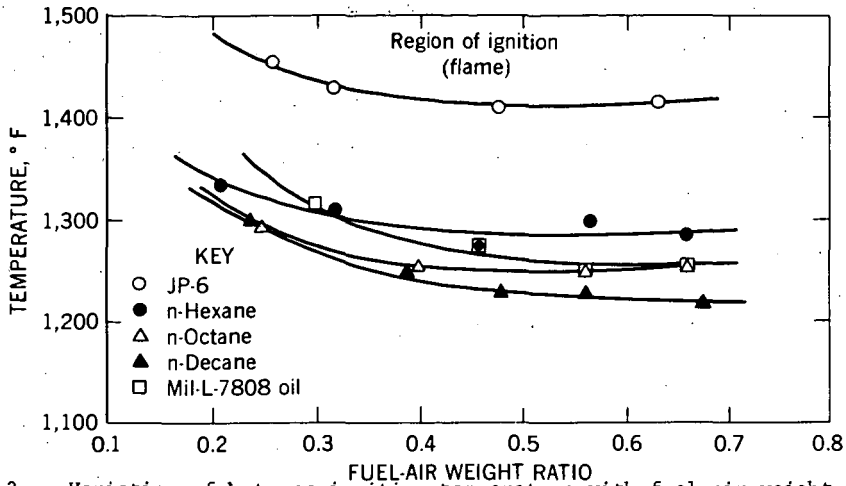


Figure 3. - Variation of hot gas ignition temperature with fuel-air weight ratio for various hydrocarbon combustible vapor-air mixtures with 1/2-inch diameter jets of hot air (Mixture flow rate - 365 in<sup>3</sup>/min).

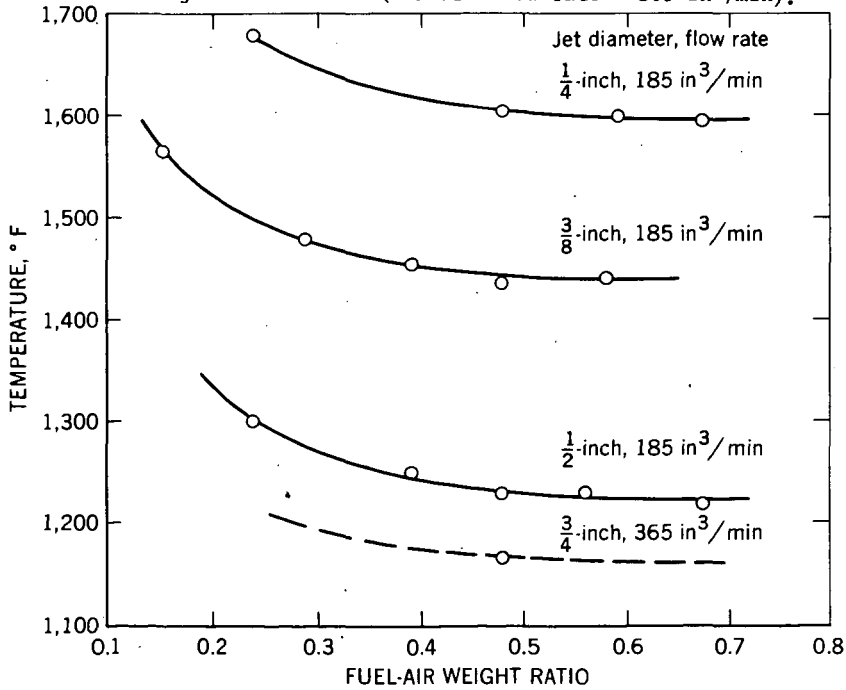


Figure 4. - Variation of hot gas ignition temperature with fuel-air weight ratio and diameter of hot air jet for n-decane vapor-air mixtures (Mixture flow rate 365 in<sup>3</sup>/min, N.T.P.)

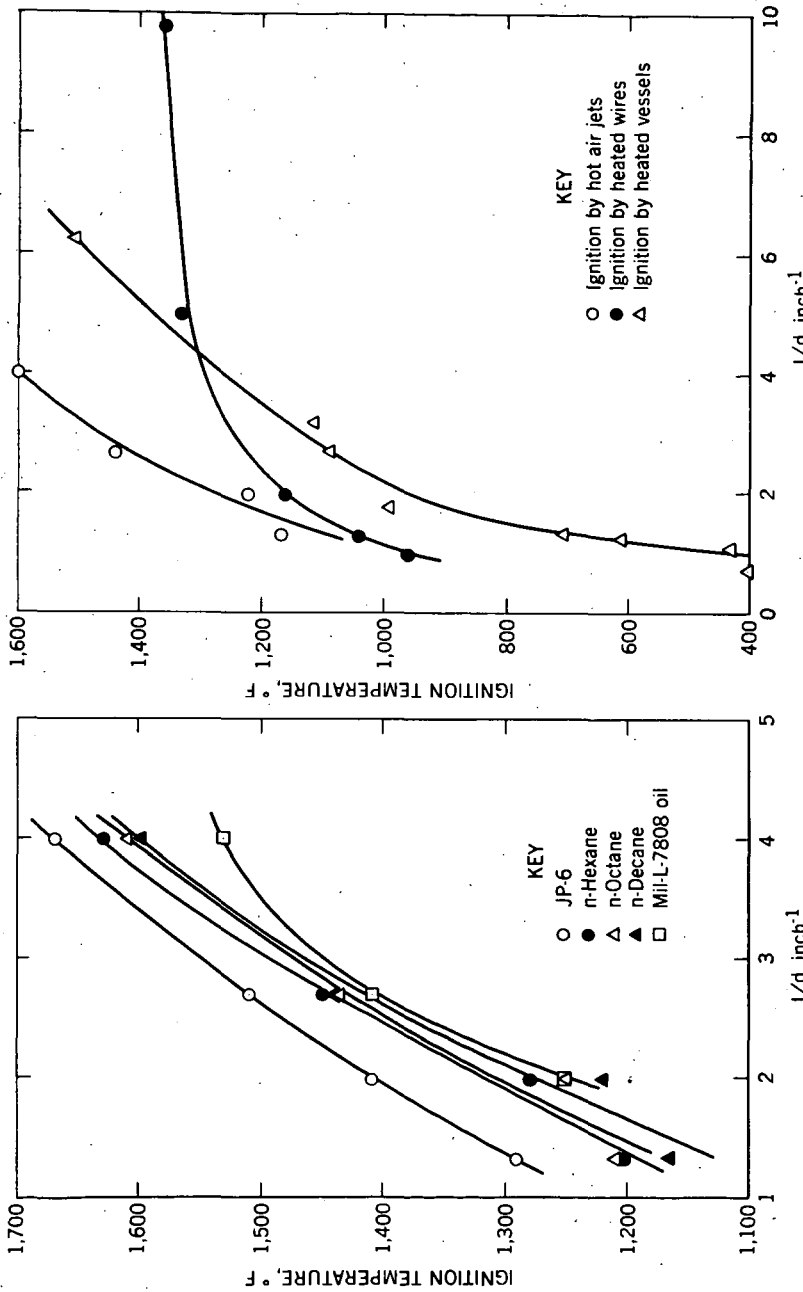


Figure 5. - Variation of hot gas ignition temperature with reciprocal diameter of hot air jet for various hydrocarbon combustible vapor-air mixtures (Flow conditions in figure 4 and table 2).

Figure 6. - Variation of hot gas and hot surface ignition temperatures with reciprocal diameter of heat source for n-decane vapor-air mixtures.

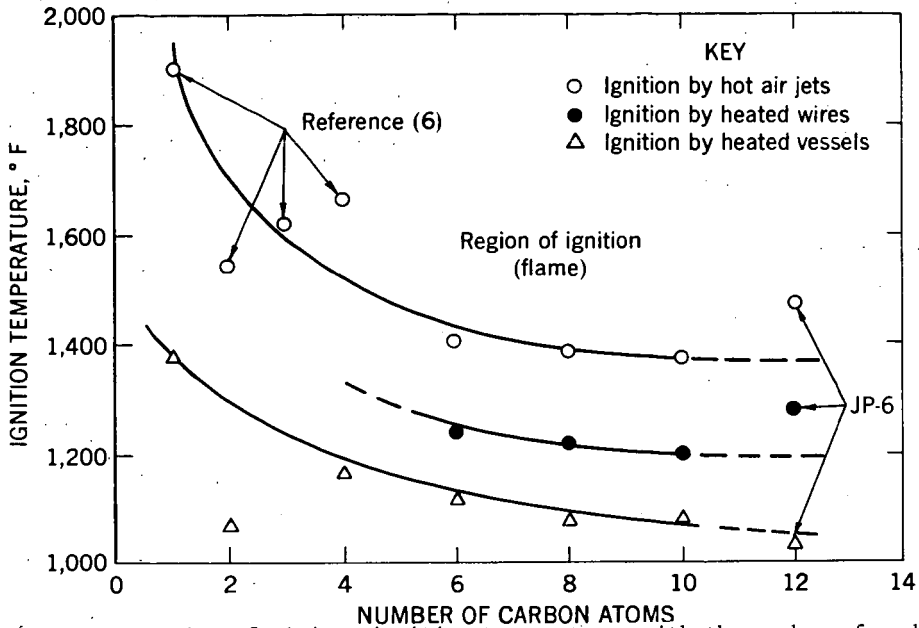


Figure 7. - Variation of minimum ignition temperatures with the number of carbon atoms for hydrocarbon (paraffin) and JP-6 vapor-air mixtures ignited with 0.4-inch diameter cylindrical heat sources.

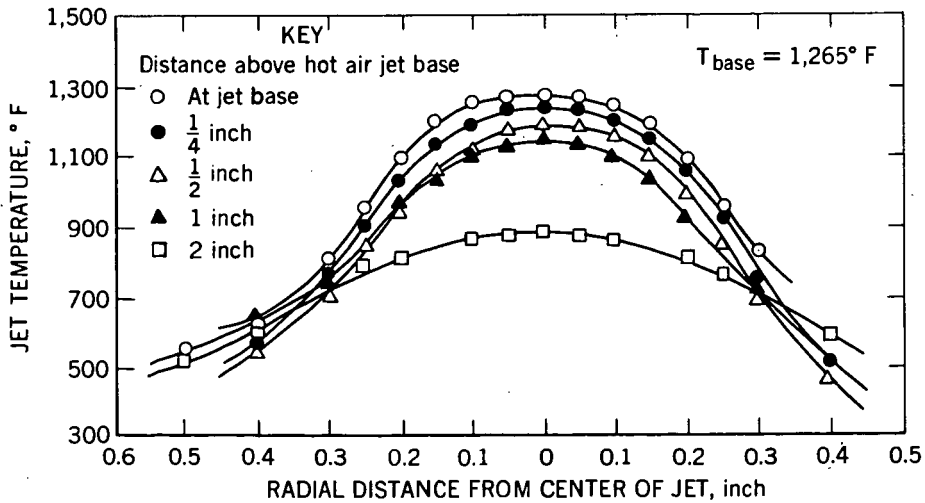


Figure 8. - Radial temperature profiles for 1/2-inch diameter jets of hot air flowing at  $185 \text{ in}^3/\text{min}$ , (N.T.P.) into preheated air at  $350^{\circ}F$ .

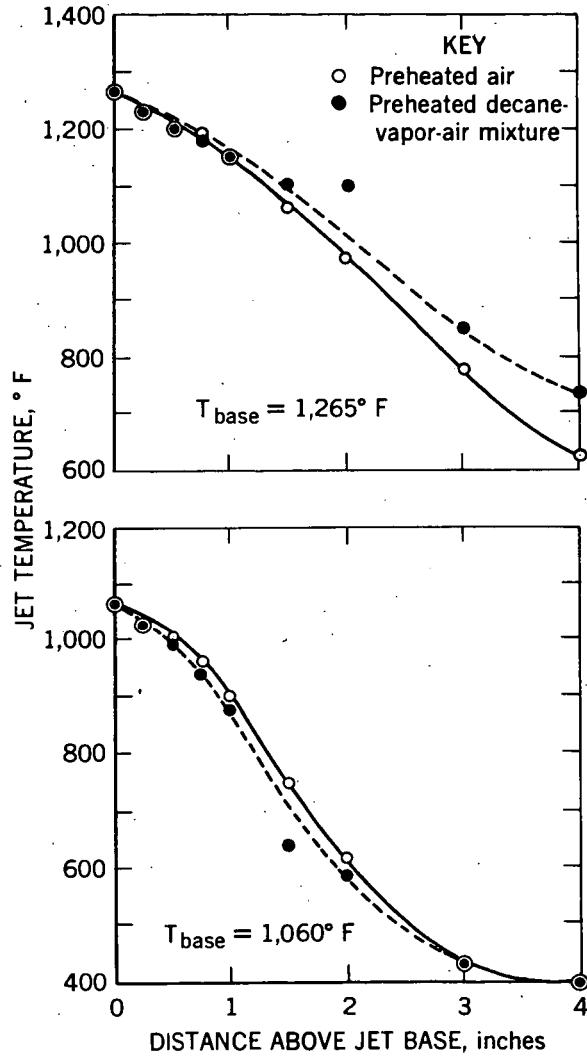


Figure 9. - Axial temperature profiles for 1/2-inch diameter jets of hot air flowing at 185 in /min, (N.T.P.) into preheated air and n-decane vapor-air mixtures at 350° F.

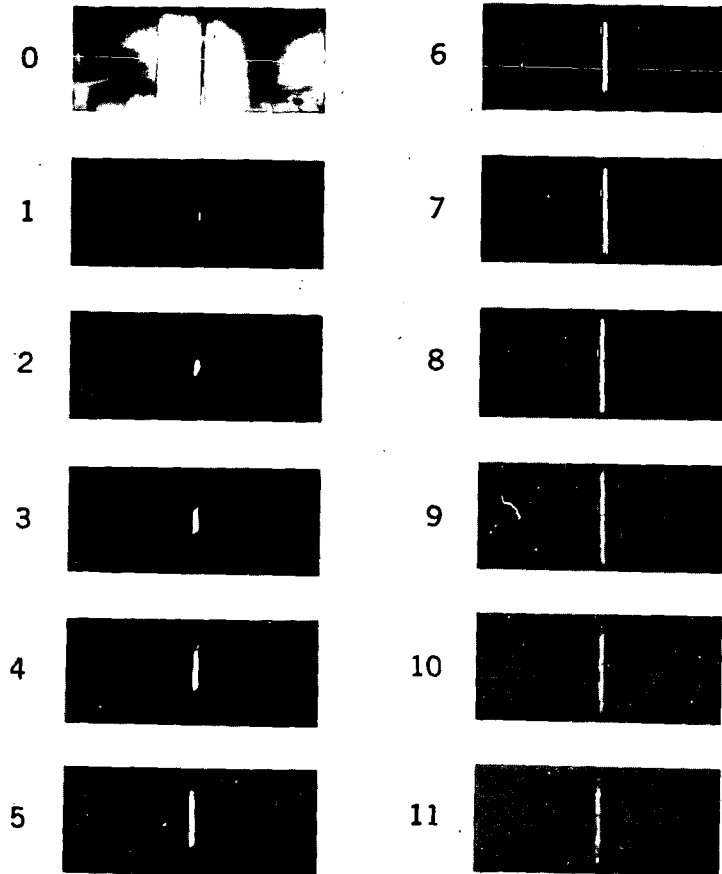


Figure 10. - Motion picture records showing the ignition of an n-octane vapor-air mixture with a 1/2-inch diameter hot air jet at 1400° F.

Jet flow rate - 185 in<sup>3</sup>/min (N.T.P.)

Mixture flow rate - 365 in<sup>3</sup>/min (N.T.P.)

Camera speed - 360 frames/sec

Scale: 1/4-inch = 5.4 inches for frames 1-11.